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EVALUATION OF CANOPY TEMPERATURE—EVAPOTRANSPIRATION MODELS OVER VARIOUS CROPS*

J.L. HATFIELD

USDA-ARS, Plant Stress and Water Conservation Research Unit, Route 3, Lubbock, TX (U.S.A.)

R.J. REGINATO and S.B. IDSO

U.S. Water Conservation Laboratory, Phoenix, AZ (U.S.A.)

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ABSTRACT

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Canopy temperatures, when measured remotely, offer a method of estimating evapotranspiration with surface energy balance models. Equations which have been developed by others have been evaluated only at a limited number of locations and with a few crops. Our study was conducted at several locations with weighing lysimeters with a variety of crops around the United States: Brawley, CA; Temple, TX; Lincoln, NE; St. Paul, MN; Fargo, ND; Kimberly, ID; and Davis, CA, to evaluate evapotranspiration utilizing canopy temperature as an input into the surface energy balance. The results show that evapotranspiration calculated from the aerodynamic resistance form of the surface energy balance was well correlated with lysimeter measurements at all locations. The errors using the surface energy balance were less than 10% in all cases for full ground cover. The Bartholic—Namken—Wiegand method was more closely coupled to net radiation than canopy temperature.

Under partial canopy cover, differences between the two models were apparent. The Bartholic—Namken—Wiegand model overpredicted when the actual evapotranspiration was above 200 W m^{-2} because of its insensitivity to surface temperature. However, the surface energy balance model exhibited only a slight overprediction above 200 W m^{-2} when a weighed composite surface temperature (representative of bare soil and crop temperature) was used. This small overprediction could be overcome by considering the soil heat flux term. There was no location bias in the surface energy balance model, which shows that it should work well at other locations.

INTRODUCTION

Evapotranspiration from a surface is a component of the partitioning of energy received by that surface. This process can be described by the familiar energy balance equation (Monteith, 1973) with expanded sensible and latent

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heat terms, as

$$Rn + G = \rho C_p \frac{(T_c - T_a)}{r_a} + \frac{\rho C_p}{\gamma} \frac{[e_s(T_c) - e_a]}{r_a + r_c} \tag{1}$$

where Rn is the net radiation ($Jm^{-2} s^{-1}$), G the soil heat flux ($Jm^{-2} s^{-1}$), ρC_p the volumetric heat capacity of air ($J kg^{-1} {}^\circ C^{-1}$), T_c the canopy temperature (°C), r_a the aerodynamic resistance (sm^{-1}), γ the psychrometric constant ($kPa {}^\circ C^{-1}$), e_s (T_c) the saturated vapor pressure at T_c (kPa), e_a the actual vapor pressure (kPa), and r_c the canopy resistance to water vapor transfer (sm^{-1}). This form of the energy balance equation has been often cited, but the difficulty in measuring canopy temperature had led to other approaches which decouple eq. 1 from a direct surface temperature measurement. The Penman—Monteith method, which includes a canopy resistance term, can be used, but it is difficult to assess the canopy resistance changes with soil water status (Monteith, 1973).

With the development of thermal infrared thermometers that are accurate and easily used, several investigators proposed the use of surface temperature in surface energy balance models to estimate evapotranspiration (Bartholic et al., 1970; Brown and Rosenberg, 1973; Jackson et al., 1977; Soer, 1980; and Sequin and Itier, 1983). These approaches have ranged from manipulation of eq. 1 to the use of empirical coefficients for deriving daily evapotranspiration from midday canopy measurements (Jackson et al., 1977). Although these approaches have been proposed only limited evaluations have been conducted. Stone and Horton (1974) compared the techniques suggested by Bartholic et al. (1970) and Brown and Rosenberg (1973) against the more traditional methods (Bowen ratio (Bowen, 1926), Penman (1948), and van Bavel (1966)) and concluded that both approaches would have promise. The authors suggested that the Bartholic—Namken—Wiegand method may be better to use because it does not require knowledge of the aerodynamic resistance which is a function of windspeed and the canopy aerodynamic properties. Verma et al. (1976), after extensive error analysis, concluded that the aerodynamic resistance method given by Brown—Rosenberg (1973) was more sensitive to errors in canopy temperature than errors in aerodynamic resistance. Blad and Rosenberg (1976) determined that either a resistance or mass transfer model utilizing remotely sensed canopy temperature would be useful in regional models.

Other comparisons over limited conditions have been conducted by Heilman and Kanemasu (1976), Heilman et al. (1976), Soer (1980), Sumayao et al. (1980), and Hatfield et al. (1983). Soer (1980) found that the evapotranspiration estimated by an energy balance model agreed 70% of the time with water balance measurements in watersheds. He stated, however, that regional estimation with remotely sensed canopy temperatures would allow for the standard error about the mean to approach zero and that this would make the estimates comparable with those from a Penman model, with both utilizing the same meteorological data base. Heilman et al. (1976) used remotely sensed canopy temperatures and found the models agreed very well after the remotely sensed canopy temperatures were corrected for atmospheric attenuation between aircraft and ground.

This experiment was implemented with the objective of evaluating evapotranspiration models which use remotely sensed canopy temperature as an input. Our report addresses the performance of the models compared to lysimeter evapotranspiration for various crops and locations in the United States.

MATERIALS AND METHODS

Description and equations

The energy balance of a surface given in eq. 1 (Monteith, 1973) can be rewritten as

$$\lambda E = Rn + G - \frac{\rho C_p}{\gamma} \frac{(T_c - T_a)}{r_a} \tag{2}$$

where λE is the latent heat of vaporization (J kg^{-1}). Sumayao et al. (1980) and Hatfield et al. (1983) showed that when the canopy was cooler than air λE would be larger than net radiation. In this method we calculate r_a from

$$r_a = [\ln (z - d)/z_0]^2/k^2 u \tag{3}$$

with z being the height (m) of observation of air temperature, windspeed, and vapor pressure above the crop surface, d the displacement height (m), z_0 the roughness length (m), k von Karmans constant (0.40), and u the windspeed (m s^{-1}). Following Monteith's (1973) correction for stability, we corrected the aerodynamic resistance as

$$r_{ac} = r_a \left(1 - \frac{n(z-d)g\,(T_c - T_a)}{Tu^2}\right) \tag{4}$$

where g is the acceleration of gravity (9.8 m s^{-2}) and T the absolute temperature (K), taken as the mean of the canopy and air temperatures. Monteith (1973) suggested that a value of 5 for n would be appropriate for field conditions. The roughness lengths and displacement heights for the crops in this study are given in Table I.

Bartholic et al. (1970) rearranged eq. 1 to obtain the following equation

$$E = \frac{Rn + G}{1 + \gamma \dfrac{(T_a - T_c)}{[e_s(T_a) - e_s(T_c)]}} \tag{5}$$

TABLE I

Location, dates, crop, ground cover, height and growth stage for the 1980 Summer Field Experiment

Location	Dates	Crop	Ground cover (%)	Height (m)	Roughness length (m)	Displacement height (m)	Midday albedo	Growth stage
Brawley, CA	01—04 June	Cotton	15	0.20	0.10	0.00	0.19	Vegetative
Temple, TX	13—17 June	Grain Sorghum	100	0.90	0.05	0.75	0.21	Vegetative
Lincoln, NE	25—29 June	Soybeans	15	0.20	0.10	0.00	0.16	Vegetative — 2nd node
St. Paul, MN	01—06 July	Alfalfa	100	0.80	0.04	0.65	0.24	Vegetative
Fargo, ND	08—13 July	Alfalfa	15	0.20	0.10	0.00	0.11	Vegetative — 2nd node
Kimberly, ID	24—29 July	Alfalfa	100	0.80	0.04	0.63	0.22	Vegetative
Davis, CA	04—05 August	Tomatoes	80	0.50	0.10	0.20	0.17	Mid-fruit set

TABLE II

Description of the lysimeter mechanism, soil type, resolution for each location and the cooperator in the 1980 field study

Location	Cooperator	Mechanism	Size (l × w × d)	Resolution (mm)	Soil type
Brawley, CA	Carl Ehlig	Platform Balance Scale	3.0 × 3.0 × 1.5 m	0.25	Imperial silty clay
Temple, TX	Joe Ritchie	Mechanical-Electronic Balance	1.0 × 1.0 × 1.0 m	0.25	Bosque fine sandy loam
Lincoln, NB	Blaine Blad	Strain Gauge	1.0 × 1.0 × 1.5 m	0.01	Sharpsburg silty clay loam
St. Paul, MN	Don Baker	Mechanical-Electronic Balance	1.5 × 1.8 × 1.2 m	0.025	Waukegen silt loam
Fargo, ND	Lynn Brun	Torsion Bar with Strain Gauge	1.5 × 1.5 × 1.5 m	0.19	Fargo clay
Kimberly, ID	Jim Wright	Scale	1.8 × 1.8 × 1.2 m	0.01	Portneut silt loam
Davis, CA	Bill Pruitt	Floating-Stillingwell	6 m (dia) × 1.0 m	0.025	Yolo silt loam

This approximation sets the surface and air at the saturation vapor pressure which limits the equation to potential evapotranspiration from an infinitely wet surface.

EXPERIMENTAL PROCEDURES

During the summer of 1980, an experiment was conducted at several locations in the western half of the United States. The locations and crop information are given in Table I. These sites were chosen because they had lysimeters with sufficient accuracy to give a reliable hourly measure of evapotranspiration. Table II describes the lysimeters at each location. In all cases except Temple the fetch requirements were met for these measurements and at Temple the lysimeter was surrounded by taller corn. The sites monitored also covered a wide range in latitude, climate and crops, which was deemed necessary to achieve our experimental objectives. At each experimental site, measurements were made of crop height and the values for roughness length and displacement height were determined from typical values reported in the literature. For those locations with less than complete ground cover the roughness length was assumed to be larger than reported values as suggested by Verma and Barfield (1979) and Hatfield (1982, unpublished data).

At each location the experimental procedure was the same, including the frequency of observation. Meteorological variables were recorded at one-minute intervals by a computer-controlled data acquisition system and the data recorded onto flexible discs. The system was housed in a mobile van which was parked near the lysimeter at each location. Observations recorded on the roof of the van were global solar radiation and longwave radiation from the atmosphere. The pyranometer was an Eppley PSP pyranometer with a WG295 filter. Longwave radiation from the atmosphere was measured with a Swissteco pyradiometer with a blackbody cup. Positioned over the lysimeter was an inverted Eppley pyranometer, a Fritschen miniature net radiometer, an aspirated dry-bulb and wet-bulb thermistor, and Gill lightchopper anemometer. The pyranometer and net radiometer were positioned 50 cm above the upper surface of the canopy and, where applicable, over the plant row. The aspirated dry- and wet-bulb thermistors and anemometers were positioned 30 cm and 130 cm above the upper surface of the canopy. These instruments were attached to the data acquisition system by a multiconductor shielded cable and were also sampled once per minute. The data were reduced and quality controlled through routines described by Hatfield et al. (1981) and reported as integrated hourly values.

Canopy temperatures were measured over the lysimeter with an infrared thermometer with a 4° fov and 8—14 μm waveband. This unit has an accuracy of $\pm$ 0.5°C and a resolution of 0.1°C. Measurements were made of the crop from each cardinal direction at about a 30° angle from the horizontal. Where the ground cover was not complete, nadir views of the soil between the rows were made along with temperatures of individual plant leaves. These measurements were made at half-hourly intervals, from 15 min before sunrise to 15 min after sunset. In the analysis procedure, the canopy temperatures were averaged to match the hourly meteorological values. In cases where incomplete ground cover was present composite scene temperature was determined by computing a weighed average based on the fraction of bare soil relative to the crop cover and their respective temperatures. This could be improved by monitoring composite scene temperature with a nadir looking angle infrared thermometer.

Lysimeter values were recorded at the same half-hourly intervals as canopy temperatures. These data were then plotted and smoothed with a three-term running average from which hourly values of evapotranspiration could be determined. It was felt that this time resolution would be adequate for all lysimeters and would insure the greatest degree of precision.

The meteorological, canopy temperature, and evapotranspiration data formed the data set from which all subsequent analyses were conducted. Evapotranspiration was calculated from eq. 2 with the inclusion of eq. 4 for the surface energy balance and eq. 5 for the Bartholic—Namken—Wiegand method. The Penman—Monteith equation was given as

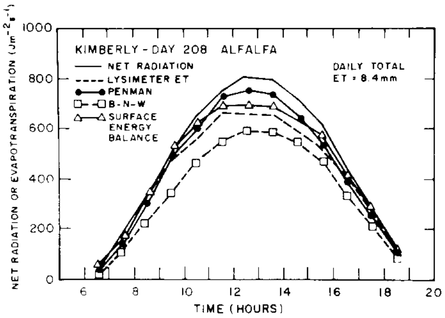
$$ET = \frac{(Rn + G) + \rho C_p \ (e_s \ (T_a) - e_a)/r_a}{\Delta + \gamma} \tag{6}$$

where Δ is the slope of the saturation vapor pressure curve (kPa $^\circ C^{-1}$) and was used with a canopy resistance term of zero in the calculations. This method provided an estimate of potential evapotranspiration for our study.

RESULTS AND DISCUSSION

For each location the Bartholic—Namken—Wiegand model (eq. 5), the surface energy balance model (eq. 2), and Penman—Monteith combination equation (eq. 6), formulas for the estimation of potential evapotranspiration, were calculated with the hourly data set. The hourly estimates were then compared with measured evapotranspiration values for each location. On each graph the integrated daily total of evapotranspiration is given as a point of reference for the reader. Only one representative day is shown for each site.

Diurnal trends of net radiation, measured evapotranspiration and the calculations of potential and actual evapotranspiration are shown in Fig. 1 for alfalfa at Kimberly. These results were for a clear day with moderate windspeeds, and the evapotranspiration values were quite high. The Bartholic—Namken—Wiegand model underestimated actual evapotranspiration values and the other models throughout the day. Evapotranspiration estimated by the surface energy balance (eq. 2) closely followed the



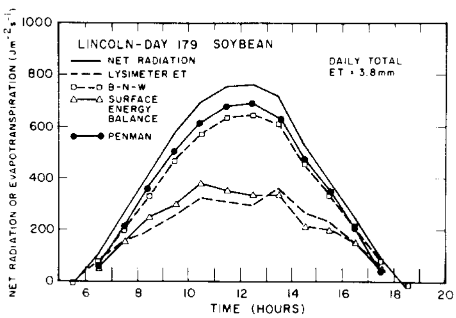


Fig. 1. Diurnal trend of net radiation and measured evapotranspiration for alfalfa and calculated evapotranspiration by the surface energy balance, Bartholic—Namken—Wiegand and Penman—Monteith combination model for Kimberly, Idaho.

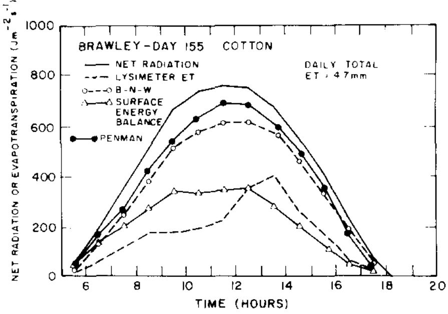
Fig. 2. Diurnal trend of net radiation and measured evapotranspiration for soybeans and calculated evapotranspiration by the surface energy balance method, Bartholic—Namken—Wiegand model, and Penman—Monteith combination model for Lincoln, Nebraska.

lysimeter values throughout the day. The differences between the surface energy balance and the measured values for Kimberly were largest on this day, although they were generally less than 10%. Estimates from the Penman—Monteith approach provide an estimate of potential evapotranspiration and are shown for the benefit of the reader. Since the purpose of the study is to compare actual evapotranspiration with the canopy temperature methods, the estimates of potential evapotranspiration will not be discussed in the remainder of the paper.

In comparing evapotranspiration estimated from the measurement of net radiation directly or from the calculation of net radiation components, differences were always less than 5%; there appeared to be no bias in the differences. For this reason, only the calculation of net radiation, as used by Soer (1980) in his evaluations, will be discussed for the remainder of the paper. In regional applications a direct measure of net radiation may not be feasible and for this reason it was felt this approach was closer to our objectives.

For the full ground cover alfalfa at Kimberly, the evapotranspiration was substantially reduced. This is illustrated by Fig. 2 for soybeans at Lincoln. Data for this day show that the conditions were generally clear with some clouds in the afternoon. Of more interest is the behavior of the measured evapotranspiration rates and the two models. The Bartholic—Namken—Wiegand model tracks the net radiation curve very closely but greatly overestimates the measured evapotranspiration rates while the surface energy balance method more closely approximates the measured values throughout the day.

In the partial canopy-cover cases at Lincoln (Fig. 2), Fargo, and Brawley (Fig. 3), the surface temperature had to be adjusted to approximate the



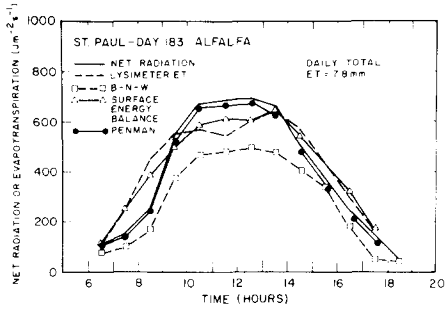


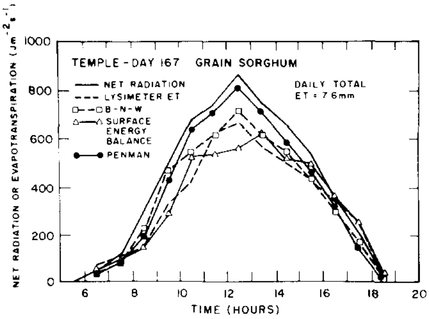
Fig. 3. Diurnal trend of net radiation, measured evapotranspiration and calculated evapotranspiration from the surface energy balance, Bartholic—Namken—Wiegand, and Penman—Monteith combination models for Brawley, California.

Fig. 4. Net radiation, measured evapotranspiration and calculated evapotranspiration by the surface energy balance, Bartholic—Namken—Wiegand and Penman—Monteith combination models for alfalfa at St. Paul, Minnesota.

composite scene temperature. This was done by averaging the soil surface area of the lysimeter they represented. Using only crop canopy temperatures, which were much cooler than the soil surface, the predicted evapotranspiration values were too high because the model assumes that the entire surface area is at this temperature. This adjustment was made for each location before the calculation of evapotranspiration with any of the methods. Soil heat flux was not measured in this study and would have to be accounted for if the model is to be applicable over large areas. The deletion of this component does not appear to introduce a large error, but it does introduce a bias in the data. Composite scene canopy temperatures would be of more use than individual plant or leaf temperatures in the estimation of evapotranspiration.

Alfalfa evapotranspiration at St. Paul exhibited a condition in which the measured values were larger than the estimated values by the Bartholic—Namken—Wiegand method (Fig. 4). The measured and calculated values from the surface energy balance method agreed very closely. For this day the measured evapotranspiration was above net radiation for the early and late part of the day and below net radiation during midday. At all times the surface energy balance model responded to the environmental conditions to estimate the measured evapotranspiration values very closely.

At Temple, the estimated evapotranspiration with the surface energy balance agreed very closely with measured values (Fig. 5). As was found in the other locations the Bartholic—Namken—Wiegand method closely followed the net radiation curves. This effect is also evident at Davis (Fig. 6) where the measured values and those predicted by the surface energy balance agreed very closely throughout the day while the Bartholic—Namken—Wiegand method, in responding predominantly to net radiation, was not affected by the late afternoon sea breeze which caused an increase in the evapotranspiration rate. This increase in evapotranspiration was affected by the



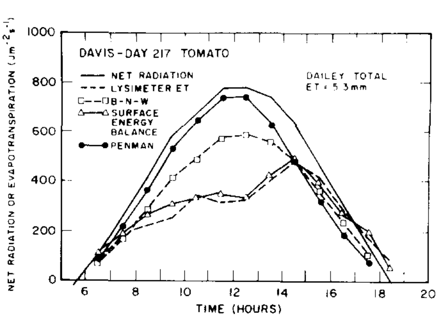
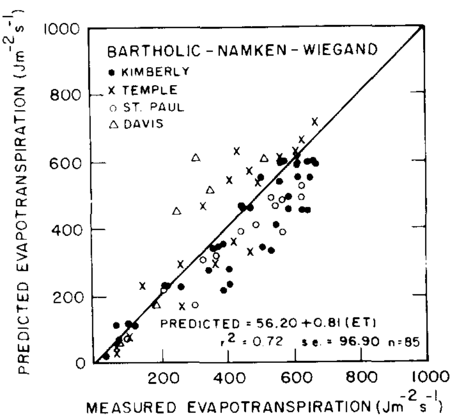


Fig. 5. Diurnal trend of net radiation, measured evapotranspiration, and calculated evapotranspiration from the surface energy balance, Bartholic—Namken—Wiegand, and Penman—Monteith combination models for Temple, Texas.

Fig. 6. Diurnal trend of net radiation, measured evapotranspiration, and calculated evapotranspiration from the surface energy balance, Bartholic—Namken—Wiegand, and Penman—Monteith combination models for Davis, California.

increase in windspeed with only a slight moderation in air temperature and vapor pressure deficit.

For all locations with at least 80% ground cover, hourly measured evapotranspiration rates were compared against values calculated from the Bartholic—Namken—Wiegand method or the surface energy balance. For each hour the aerodynamic resistance was stability corrected via eq. 4. The comparisons for the Bartholic—Namken—Wiegand model are shown in Fig. 7 for Kimberly, Temple, St. Paul, and Davis. There is generally a good fit about the 1 : 1 line, but the standard error is almost 100 J m^{-2} s^{-1}. The predictions



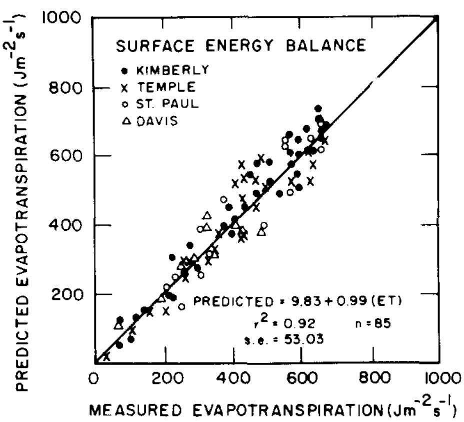


Fig. 7. Measured evapotranspiration from lysimeters at Kimberly, Indiana; Temple, Texas; St. Paul, Minnesota; and Davis, California, compared with calculated evapotranspiration by the Bartholic—Namken—Wiegand model.

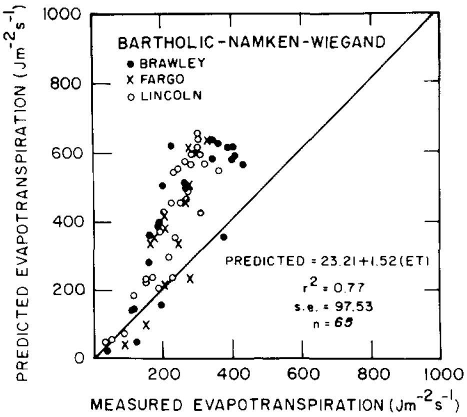
Fig. 8. Measured evapotranspiration from lysimeters at Kimberly, Indiana; Temple, Texas; St. Paul, Minnesota; and Davis, California compared to calculated evapotranspiration by the surface energy balance model.

could also be grouped by location — at St. Paul and Kimberly the model tended to underpredict, while at Temple and Davis there was an overprediction. Because net radiation is the main driving factor in this model, predictions of evapotranspiration are insensitive to canopy temperature, as shown by Hatfield et al. (1983).

Measured and predicted evapotranspiration by the surface energy balance (eq. 2) showed an extremely good fit for all of the locations with full-ground cover (Fig. 8). There was not any location bias, and the fit was good for the entire range of data. From the good agreement between predicted and measured values, the stability adjustment in aerodynamic resistance appears adequate. The lack of location bias indicates that there is no need for a local wind or crop factor, which makes this model more widely applicable. The standard error about the line was about $50\,J\,m^{-2}\,s^{-1}$, which would be an acceptable error over the range of the data. There also was not an overestimation at the higher evapotranspiration rates, as was found by Heilman et al. (1976). These results show that either the surface energy balance model with canopy temperature and net radiation, either directly measured or calculated from its components, would provide a reliable and accurate estimate of the evapotranspiration of a cropped surface.

During the early stages of crop growth, ground cover is minimal for most crops and in many locations, full ground cover is not obtained. As seen in Table I, three locations we visited had only 15% ground cover, so we were able to evaluate the two evapotranspiration models for the partial canopy cover condition. Results for the Bartholic—Namken—Wiegand model are given in Fig. 9. As shown in Fig. 2, this model overestimates the measured evapotranspiration rate at all values above $200\,J\,m^{-2}\,s^{-1}$. Below this level the measured values are very closely tied to the net radiation. At early morning and late evening hours the evapotranspiration is closely tied to radiation availability and the soil and canopy temperatures are relatively close to air temperature. During midday, however, the evapotranspiration process over the entire surface is low or negligible for the soil as compared to the crop and the relative disagreement decreases as the fraction of soil cover decreases.

Agreement between measured and calculated evapotranspiration by the surface energy balance method, when composite surface temperature was used, was much better than the Bartholic—Namken—Wiegand method for partial canopy cover (Fig. 10). When only crop canopy temperature was used for these sites the slope was 1.7 with $R^2 = 0.51$. There is still considerable scatter about the 1 : 1 line, and the model tends to overpredict the measured amounts. This overprediction could be accounted for in eq. 2 if the soil heat flux term were included in the analysis. It is possible that this problem could be overcome by using the change in the soil surface temperature from one hour to the next to approximate a change in heat storage. This aspect will require further investigation before the model can be applied throughout a growing season. Measured composite temperatures would possibly improve the model over the weighted average which was utilized in this study.



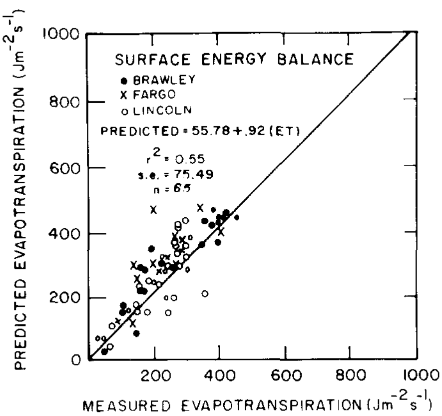


Fig. 9. Measured evapotranspiration from partial canopy cover crops on lysimeters at Brawley, California; Fargo, North Dakota; and Lincoln, Nebraska compared to calculated evapotranspiration by the Bartholic—Namken—Wiegand model.

Fig. 10. Measured evapotranspiration from partial canopy cover crops on lysimeters at Brawley, California; Fargo, North Dakota; and Lincoln, Nebraska compared to calculated evapotranspiration by the surface energy balance model.

SUMMARY AND CONCLUSIONS

Canopy temperature as an input to surface energy balance models provides a method for estimating actual evapotranspiration from a surface. Surface energy balance models proposed by Brown and Rosenberg (1973) and Soer (1980) performed well for all locations and crops in this study. The best agreement between measured and predicted evapotranspiration rates was for full canopy cover, although a composite surface temperature (soil and plant) improved the fit between predicted and actual evapotranspiration values. Diurnal plots of the data showed that the Bartholic—Namken—Wiegand method was driven mainly by net radiation and had a large error in estimating actual evapotranspiration, particularly in situations with partial canopy cover.

Inclusion of canopy temperature with other meteorological data does not make a complete remote sensing approach but it does allow for dynamic coupling between the plant and atmosphere. Ground-based net radiation, air temperature and windspeed are still needed as model inputs. Any collection of surface temperature from an air or spacecraft would represent an instantaneous evapotranspiration rate and this technique would have to be applied over a complete day to improve the utility of the information for agricultural management. Jackson et al. (1983) proposed a method based on latitude, time-of-day and time-of-year which adjusts one time-of-day measurements to daily totals. This approach, along with an estimation of seasonal changes in the canopy aerodynamic properties, will have to be evaluated over a complete growing season to provide a rigorous test of the model's limitations. These results indicate that the surface energy balance with canopy temperature inputs is an accurate and reliable method of obtaining actual evapotranspiration from a crop surface.

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